The Relative Amplitude of Vowel Formants for Vowels in Asymmetrical Consonant Contexts

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Distinction in Speech and Hearing Science in the Undergraduate Colleges of The Ohio State University

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ABSTRACT

The objective of this research is to characterize the role of the relative intensity of speech segments in the auditory processing of vowels and consonants within larger prosodic domains such as words. This project focuses on vowels and investigates the relative amplitude of vowel formants as a possible cue when listeners make phonemic and sub phonemic distinctions. The specific goal of this project is to examine the acoustic pattern of the relative amplitude of formants in the production of selected co-articulated vowels. A follow up study will examine the auditory effect of formant level variations on listeners' decision about vowel quality and the intelligibility of words. This honors thesis project supplements a much larger acoustic study, which is a partial replication and extension of an early study by House and Fairbanks (1953) examining vowel intensity in different consonant contexts.

The present research question is how the distribution of intensity across vowel spectra in asymmetric consonant contexts (C_1VC_2 where $C_1 \neq C_2$) differs from that in symmetrical contexts (C_1VC_1 where $C_1 = C_1$). Recordings of vowels in both symmetrical and asymmetrical contexts were obtained from adult Midwestern American English speakers who participated in the larger study. The acoustic data obtained includes measurements of the vowel duration, vowel intensity peak (rms), relative location of the rms intensity peak, overall vowel intensity, and the relative amplitude of formants 1-4. This overall research project aims to provide comprehensive analysis of vowel intensity

and its role in the processing of the speech signal. It is expected that the internal distribution of intensity will differ among the vowels, depending on the frequency of the formants. However, whether and how this distribution changes in the different consonantal contexts is the question that will be addressed.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION AND BACKGROUND

The relationship between the acoustic (i.e., spectral) characteristics of vowels and their perceived phonetic quality is quite complex. Over the past 50 years a great deal of effort has been put forth in attempting to examine and better understand the fundamental frequency, formant frequencies, and duration of vowels. The most identifiable acoustic characteristic of a vowel is its formant frequency patterns. The landmark acoustic perception study of Peterson and Barney (1952) measured formant frequencies F1-F3, formant amplitudes, and the fundamental frequency of ten American English vowels in /h_d/ contexts spoken by 33 men, 28 women, and 15 children. The /h_d/ tokens were then presented to listeners for identification, showing the relationship between formant patterns and vowel identification.

Hillenbrand, Getty, Clark, and Wheeler (1995) conducted a replication of Peterson and Barney (1952) having 45 men, 48 women, and 46 children produce the American English vowels /i, ɪ, ɛ, e, æ, ɑ, ɔ, ʊ, u ʌ/ in /h_d/ syllables. They then measured vowel duration, fundamental frequency, and frequencies of formants F1-F4 using LPC analysis at a maximally steady (sinusoidal) point. The formant frequencies of a vowel vary because of vocal tract configuration, changes in vocal tract shape, which is a non-uniform acoustic tube closed at one end. This produces different vowel quality or resonance quality, as well as the context in which they are spoken. These studies identified the role that vowel duration and formant frequencies have in producing different vowels. However little information has been compiled regarding relative vowel intensity, specificlly vowel amplitude variation in naturally occurring speech.

In another study, Hillenbrand, Clark, and Nearey (2001) looked at vowel identification and spectral patterns when varying consonant environments. Eight American English vowels (/i, ɪ, ɛ, æ, ɑ, ʊ, u ʌ/), seven initial consonants (/h, b, d, g, p, t, k/), and six final consonants (/b, d, g, p, t, k/) were recorded in C_1VC_1 (C_1VC_1 where $C_1 = C_1$) and $C_1V\ C_2$ (C_1VC_2 where $C_1 \neq C_2$)contexts rather than the standard /h_d/ environment for six men and six women. Shifts in F1-F3 (measured every 5 ms during production) occurred in rounded vowels in alveolar environments. In C_1VC_1 contexts voiced stops in both initial and final positions may lengthen the vowel by 20-40ms. Their study on the effects of consonant environment on vowels also found that the initial consonant impacts the vowel place of articulation.

Consonant context greatly impacts the distinguishing vowel features, which House and Fairbanks defined in their 1953 study analyzing C_1VC_1 (C_1VC_1 where $C_1 = C_1$) contexts. House and Fairbanks (1953) reported measurements of duration, fundamental frequency (F0), and relative power (amplitude) for six American English vowels /i, e, æ, ɑ, a, o, u/. The vowels were produced in symmetrical stressed Consonant Vowel Consonant (C_1VC_1) syllables with twelve consonants /p, t, k, b, d, g, f, v, s, z, m, n/ differing in voicing, manner, and place of articulation. Each syllable was prefixed by unstressed [hə], which resulted in a disyllabic stimulus token stressed on the second target syllable. Ten male speakers were carefully selected from a larger pool of students enrolled in elementary speech courses for the duration, fundamental frequency, and intensity data. The stimuli were spoken in random order into the microphone mounted on a boom stand, approximately 12 inches from the speaker's mouth. The intensity measurements were made at the maximum level of each syllable as read from a sound level meter. The measurements were converted to relative power to normalize the data across speakers due to the differences in individual loudness levels.

Based on the relative power means averaged across all consonant contexts, the vowels fell in two groups: those greater in power such as /o, e, u/ and those lesser in power such as /i, ae, a/. The differences due to the manner of articulation showed that vowels in the fricative contexts (/f, v, z, s/) were more intense than in the stop contexts (/p, t, k, b, d, g/). Finally, the data was inconclusive regarding the effects of consonantal place of articulation. As a general tendency, vowels in the velar contexts (/k, g/) were lesser in power than those in the alveolar contexts (/ t, d, s, n, z/), which were greater in power than vowels in the labial contexts (/p, b, f, v/) (Jacewicz & Fox in preparation for publication).

This benchmark study however, had limitations with regard to vowel intensity, which will be addressed in a portion of the current investigation. This is part of a larger three-year acoustic study replicating and extending the earlier work on vowel intensity by House & Fairbanks (1953). The extension of the House and Fairbanks' study involves examination of intensity distribution across the vowel spectrum. The goal is to establish whether and how vowel intensity is distributed over the first four formants and if this distribution varies with consonantal context. Only selected sets of C_1VC_2 contexts were examined because of the desire to represent real word situations. There are limited sets of configurations, which produce real English words. This study looks at overall rms amplitude, amplitude of rms peak along with its relative location in the vowel and frequency measurements for the first four formants. The vowel amplitude results focus on the comparison of intensity variations for vowels in selected symmetrical vs. asymmetrical consonant contexts, which has not yet been thoroughly examined. The following question is raised: If a vowel shows significant variation in distribution of energy across the spectrum as a function of context, which consonants impact the vowel most?

This research aims to provide comprehensive analysis of vowel intensity and subsequently its role in the processing of speech signal. It is expected that the internal distribution of intensity will differ among the vowels, depending on the frequency of the formants. However, whether and how this distribution changes in different vowel contexts is an empirical question. There is an indication from past research that particular parts of the vowel spectra will be affected differently as a function of different contexts (e.g., Miller, 1953; Fant, 1956; Lindqvist, J. and Pauli, 1968; Ainsworth, 1972; 1981; Aaltonen, 1985). The present research will make it possible to examine the acoustic relevance of these changes to vowel processing and the intelligibility of words. It needs to be mentioned that formant frequencies are generally assumed to be the principal determinants of vowel quality. Other cues such as vowel duration, fundamental frequency, relative overall intensity, and even the amplitude of the formants have been considered as secondary factors in preserving vowel identity.

However, it has been demonstrated that duration is of significant importance in vowel processing and identification (see Ainsworth 1972, 1981; Mermelstein, 1978; Gottfried and Beddor, 1988; Whalen, 1989). In addition support for the role of fundamental frequency in vowel identification has also been found (e.g., Nearey, 1989; Whalen and Levitt, 1995; Katz and Assmann, 2001). In contrast, little is known about the influence of relative intensity. Surprisingly, both overall amplitude and amplitude of formants have not been explored systematically since early work in vowel perception.

The acoustic project data will provide critical information about how the changes in relative formant amplitudes resulting from asymmetrical consonant contexts affect intelligibility of words. Intelligibility is a property of speech communication involving meaning. Distortion of the intensity relations due to manipulations in the amplitudes of formants for vowels in contexts may influence listeners' interpretation of minimally contrastive words such as *beat* and *bit*. The data from the project will be used in preparing subsequent perception experiments planned for the larger study, involving manipulations in formant amplitudes using speech synthesis.

CHAPTER 2

METHODS

Participants:

This project utilizes the recordings of twenty speakers (ten men and ten women) of Midwestern American English with no known history of speech disorders. The participant recordings were made during the first stage of the larger study. Age of the speakers ranged between 16 and 36 years (mean 23.5, st. dev. 4.39). Fourteen speakers were born and raised in Ohio, four in Michigan, and two in Wisconsin. The speakers were phonetically untrained and were either high school or university students enrolled in a variety of majors at The Ohio State University. The recorded corpus of data consists of syllables spoken in symmetrical C_1VC_1 and asymmetrical C_1V C_2 contexts. I have analyzed a subset of the recorded data from all twenty speakers in four selected asymmetrical contexts.

Test Stimuli:

Eight American English vowels were selected: /i, ɪ, ɛ, æ, ɑ, ɔ, ʊ, u/. The selected consonant set consisted of ten oral consonants /p, t, k, b, d, g, f, v, s, z/ as in House and Fairbanks (1953). The C_1VC_2 tokens were produced as monosyllables, without the prefix [hə], in a stressed position located in a short sentence "It's a …… .". Like House and

Fairbanks (1953) the syllable with the target vowel was stressed and was preceded by an unstressed and reduced syllable. This modification was introduced merely for practical reasons as the phonetically untrained speakers found it difficult to read a nonsense word with the [hə] prefix. Three sets of minimal pairs for front vowels were used 'beat, bit, bet, bat,' 'feed, fid, fed, fad,' 'seat, sit, set, sat'. The minimal pairs for back vowels include 'cooed, could, cawed, cod', 'fuit, foot, fought, fot', 'suit, soot, sought, sot'. Minimal pair being defined as two words with the same number of phonemes in which the phonemes only differ by one phoneme. Some nonsense words were included due to the limitation of using real words from the lexicon.

Acoustic analysis:

In this thesis, only selected contexts were chosen form the entire set of minimal pairs shown in Table 2.1.

Table 2.1. Vowels and selected consonant contexts used in this study.

i	ɪ	ɛ	ae	u	ʊ	ɔ	a
b_t b_b t_t s_s	b_t b_b t_t s_s s_t	b_t b_b t_t s_s s_t	b_t b_b t_t s_s	t_t s_s s_t f_f	t_t s_s s_t f_f f_t	t_t s_s s_t f_f f_t	t_t s_s s_t f_f

Vowel Duration

Vowel duration for this study represents the measured length of time in milliseconds from the time of vowel onset to vowel offset. For measurement purposes vowel onset is defined at the point where the sinusoidal shape of the waveform becomes apparent. Vowel offset is defined as the point where the periodicity of the vowel waveform ceases.

Intensity of rms Peak

The intensity of the rms peak, which is the point of greatest acoustic power centered over a 20 ms window, was isolated using a computer program written in Matlab (by, Dr. Robert Fox). I determined vowel onsets and offsets from the waveform utilizing Adobe Audition speech analysis software

Location of rms Peak

Peak location is a measure of the location of the center of the rms peak relative to the vowel's onset. Usually, rms peak is located before temporal vowel midpoint but its precise location may vary with consonant context of the vowel.

Overall Amplitude

Overall amplitude is the average rms amplitude of the vowel. Both rms peak location and overall amplitude have been determined by output from another Matlab program written for this project. My measurements of vowel onsets and offsets served as input for this Matlab program.

Formant Frequencies

Amplitude and frequency of the first four formant curves were analyzed using the speech analysis program TF32 and a separate program in Matlab to determine measurements for each formant in a vowel. The measurements made for each acoustic characteristic parameter have been entered in Excel spreadsheets, converted to SPSS data files, and mean values were then obtained.

CHAPTER 3

DISSCUSSION AND RESULTS

Vowel Duration

Table 3.1 displays individual vowel duration means for male and female speakers. The symmetric b_b context in front vowels and s_s context in back vowels have the longest vowel duration of the contexts selected for the study. The asymmetric b_t and s_t contexts produce the shortest duration for all front vowels. The asymmetric s_t and f_t contexts display nearly identical vowel durations in back vowels. These two contexts produce the shortest vowel duration for back vowels /u, ɔ, ʊ/. Unexpectedly for the back vowel /a/ in t_t and f_f contexts produced the shortest vowel duration. The C_1VC_2 contexts clearly have produced shorter vowel durations than all of the C_1VC_1 contexts across the vowel spectra shown in figure 3.1. Vowel duration in asymmetric contexts does not appear to average the durations of the initial and final consonant or mimic the duration of symmetric data. It is unclear whether the consonant location in a syllable, initial or final impacts vowel duration in a systematic way.

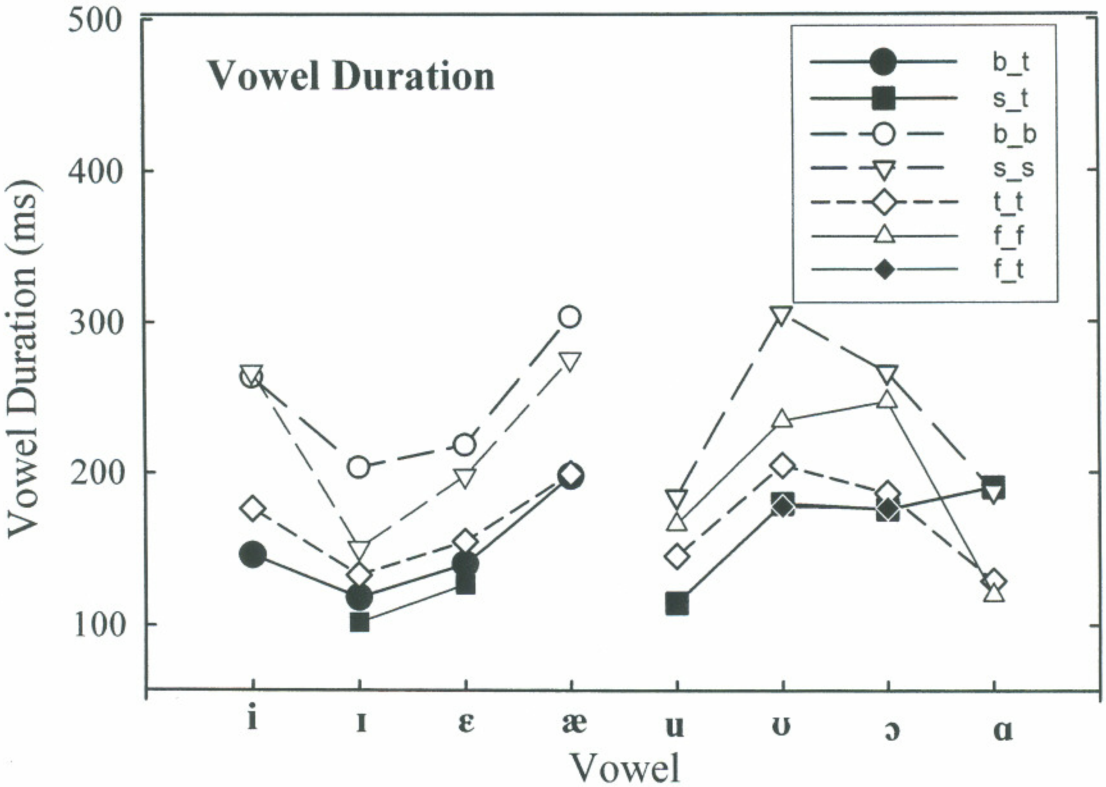
Table 3.1, a. Vowel duration means (ms) for male speakers.

vowel	b_t	b_b	t_t	s_s	s_t	f_f	f_t
i	149	238	164	233			
ɪ	119	180	125	142	104		
ɛ	138	192	153	188	127		
ae	194	280	196	253			
u			131	158	167	152	
ʊ			198	271	177	221	174
ɔ			174	239	175	218	172
a			129	172	171	118	

Table 3.1, b. Vowel duration means (ms) for female speakers.

vowel	b_t	b_b	t_t	s_s	s_t	f_f	f_t
i	143	289	189	301			
ɪ	117	227	141	159	100		
ɛ	141	245	157	208	126		
ae	201	327	203	298			
u			160	211	113	181	
ʊ			214	350	183	251	182
ɔ			198	291	178	273	183
a			129	204	210	121	

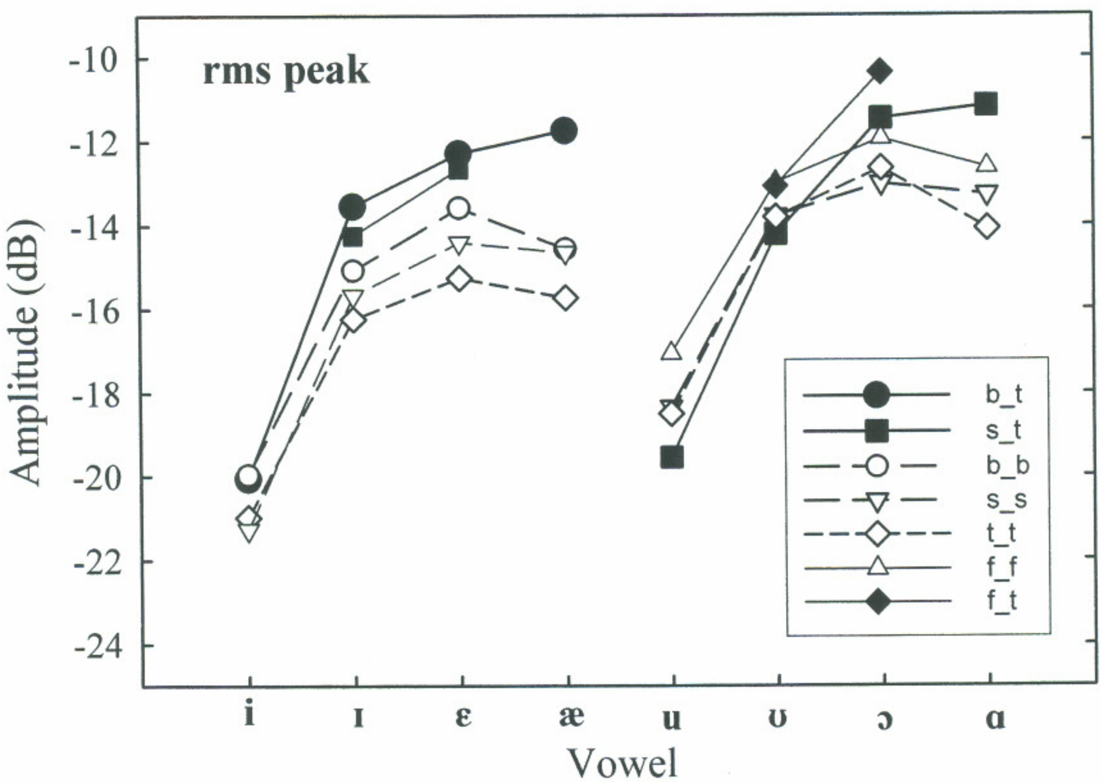
Figure 3.1. Mean vowel duration for male/female speakers. Showing greater vowel duration of C_1VC_1 contexts in comparison to C_1VC_2.



Intensity of rms Peak

Intensity peaks were strongest for asymmetrical contexts except for the vowels /i, u, ʊ/. In the s_t context the rms peak for /u, ʊ/ had the least amount of power but then became the more powerful with the vowels /ɑ, ɔ/. The mean rms intensity peak data shown in figure 3.2 closely resembles the overall amplitude displayed in figure 3.4. Similar to the House and Fairbanks (1953) results, vowels in fricative contexts (/f, s/) were more intense than in stop contexts (/b, t/). However when /b/ and /t/ are used to generate an asymmetric context the rms peak intensity has the greatest amplitude of the front vowels.

Figure 3.2. Mean intensity of rms peak for male/female speakers.



Location of rms Peak

Symmetric fricatives s_s in front vowels and f_f in back vowels cause a significant delay in the location of rms amplitude peak. The f_f and s_s symmetric consonant contexts have the most impact on the isolation of rms peak, which occurs approximately 10 ms later in a vowel than other contexts peaking at 80 ms. The C_1VC_2 f_t context came closest to the C_1VC_1 f_f context in back vowel rms peak location. There is an earlier peak location in plosive consonants /b/ and /t/ because of pressure build up in stop articulation evident in figure 3.3. The t_t context stays similar in both front and back vowels.

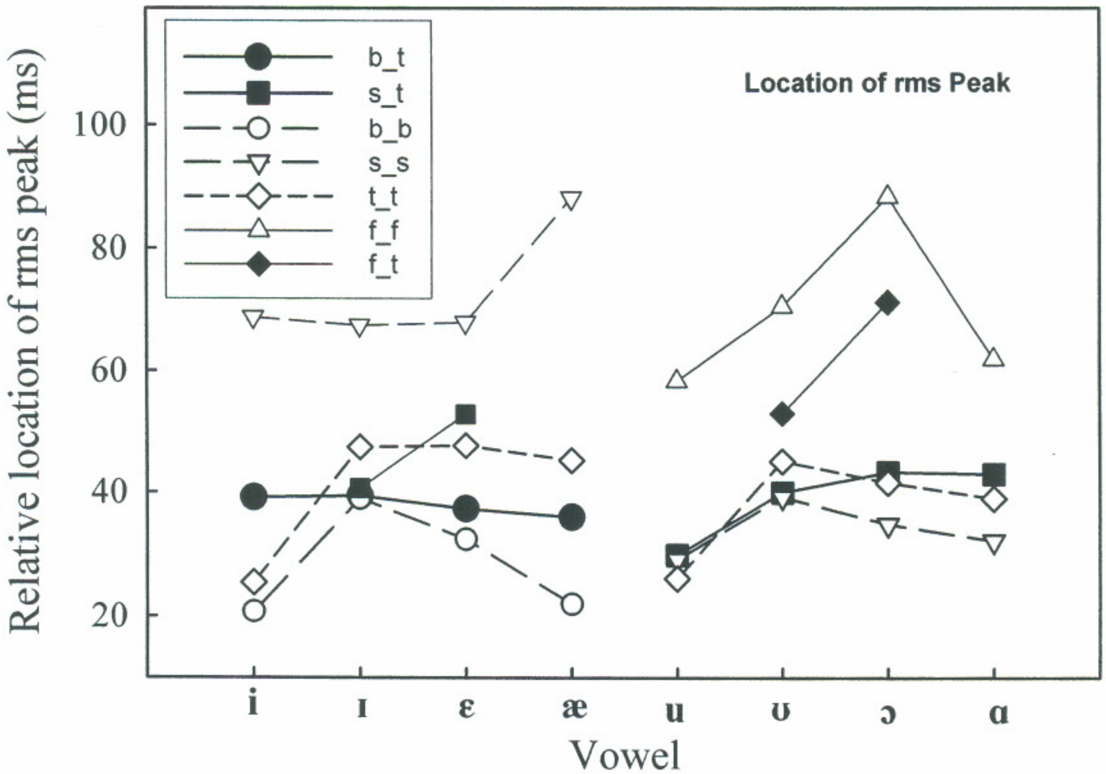
Table 3.2. Mean location of rms peak (ms) from vowel onset for male/female speakers.

vowel	b_t	b_b	t_t	s_s	s_t	f_f	f_t
i	87	46	42				
ɪ	51	77	53	54	44		
ɛ	50	74	59	61	51		
ae	62	73	82				
u			43	57	39	49	
ʊ			47	54	42	49	51
ɔ			68	98	80	77	75
a			61	69	76	53	

Male rms peak location (ms)

vowel	b_t	b_b	t_t	s_s	s_t	f_f	f_t
i	62	59	50				
ɪ	42	79	70	81	36		
ɛ	55	64	80	75	55		
ae	78	57	98				
u			61	62	40	68	
ʊ			87	87	45	92	55
ɔ			99	106	74	103	67
			83	94	76	70	

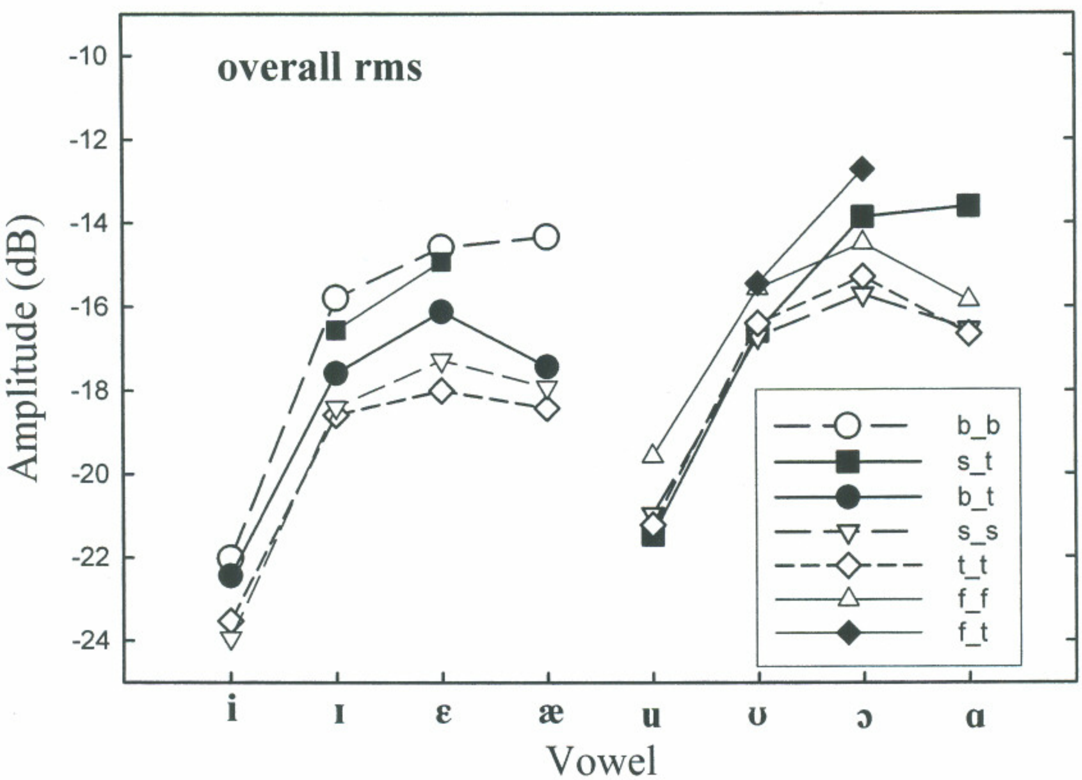
Figure 3.3. Mean location of rms peak for male/female speakers.



Overall Amplitude

Comparing the amplitude of different contexts and how overall intensity changes from one context to another is done in figure 3.4. Generally, overall rms amplitude is higher for asymmetric contexts (f_t, s_t) in back vowels. There is a significant dB increase for specific back vowels with fricative consonants such as; /fɔt/ which is the most intense at -13 dB. Unusually the b_b context had a very high overall amplitude, greater than the asymmetric contexts, possibly due to a plosive on both sides of the vowel. The overall rms amplitude figure 3.4 is nearly identical to the data displayed in the rms peak amplitude figure 3.2.

Figure 3.4. Mean overall rms amplitude for male/female speakers.



Formant Frequencies

The specific format frequency data is listed in Table 3.3 for front vowels and Table 3.4 for back vowels. Figures 3.5-3.8 show how formant frequencies are impacted by the vowel context. Male and female formant frequencies for the front vowels (/ε, æ/) were similar in all consonant contexts. Formants were most affected by consonant context in the back vowels /u/ and /a/. The fricative /f/ significantly lowered the F2 frequency in the f_f context evident in figures 3.6(a) and 3.8(a). The f_f and f_t contexts of the vowel/ʌ/ in figure 3.6(b) and 3.8(b) both had lower second formant frequencies. There is a clear distinction between symmetric and asymmetric contexts in F2-F4 for the vowel /i/. The expected result of internal intensity distribution varying among vowels because of formant variation was accurate.

Table 3.3. Front vowel F0 and F1-F4 for male/female speakers.

			i	ɪ	ε	ae
F0	M	b_t	155	153	147	140
		b_b	139	132	128	127
		t_t	149	144	134	128
		s_s	148	141	136	129
		s_t		160	154	
	F	b_t	233	227	220	218
		b_b	232	214	213	209
		t_t	247	218	211	207
		s_s	239	218	217	210
		s_t		241	227	
F1	M	b_t	314	473	620	701
		b_b	324	487	628	677
		t_t	330	516	672	764
		s_s	343	485	634	711
		s_t		478	628	
	F	b_t	327	524	806	952
		b_b	357	546	773	881
		t_t	319	603	871	1031
		s_s	351	616	832	956
		s_t		518	798	
F2	M	b_t	2257	1876	1735	1758
		b_b	2138	1783	1653	1686
		t_t	2281	1824	1741	1761
		s_s	2133	1716	1637	1690
		s_t		1824	1703	
	F	b_t	2875	2289	2120	2054
		b_b	2742	2210	2013	2031
		t_t	2947	2287	2081	2017
		s_s	2742	2145	1960	1975
		s_t		2199	2080	
F3	M	b_t	2811	2613	2560	2535
		b_b	2670	2550	2579	2546
		t_t	2854	2569	2574	2478
		s_s	2683	2572	2590	2550
		s_t		2620	2572	

F4	F	b_t	3329	3090	3050	2934
		b_b	3179	3044	3020	2953
		t_t	3379	3127	3033	2891
		s_s	3211	3070	3024	2907
		s_t		3126	3039	
	M	b_t	3407	3409	3429	3464
		b_b	3343	3391	3461	3387
		t_t	3386	3415	3434	3331
		s_s	3412	3435	3390	3291
		s_t		3485	3584	
	F	b_t	4160	4155	4101	4005
		b_b	4014	4201	4190	4199
		t_t	4279	4243	4259	4035
		s_s	3965	4275	4181	4043
		s_t		4309	4101	

Table 3.4. Back vowel F0 and F1-F4 for male/female speakers.

			u	ʊ	ɔ	a
F0	M	s_t	169	162	144	144
		s_s	148	138	131	128
		t_t	149	146	130	126
		f_f	148	139	130	127
		f_t		158	147	
	F	s_t	253	244	222	225
		s_s	242	226	207	214
		t_t	247	217	209	215
		f_f	237	219	207	216
		f_t		242	223	
F1	M	s_t	349	484	699	723
		s_s	364	497	675	727
		t_t	368	520	701	776
		f_f	389	510	672	743
		f_t		508	693	
	F	s_t	412	521	912	996
		s_s	458	602	900	965
		t_t	439	641	926	1015
		f_f	479	647	892	945
		f_t		578	905	
F2	M	s_t	1759	1386	1146	1249
		s_s	1631	1332	1065	1266
		t_t	1705	1362	1065	1258
		f_f	1269	1089	992	1158
		f_t		1126	1139	
	F	s_t	2099	1746	1416	1537
		s_s	2025	1663	1349	1435
		t_t	2067	1690	1288	1472
		f_f	1573	1346	1242	1376
		f_t		1503	1302	
F3	M	s_t	2382	2533	2532	2518
		s_s	2350	2455	2541	2558
		t_t	2323	2447	2524	2489
		f_f	2293	2501	2533	2631

		f_t		2466	2616	
	F	s_t	2887	3008	2859	2908
		s_s	2870	2984	2949	2899
		t_t	2819	2933	2848	2793
		f_f	2837	2973	2997	2841
		f_t		2964	2869	
F4	M	s_t	3260	3345	3292	3331
		s_s	3257	3223	3295	3286
		t_t	3222	3199	3294	3418
		f_f	3112	3188	3322	3423
		f_t		3206	3473	
	F	s_t	3993	3964	3744	3869
		s_s	4046	4074	3830	3809
		t_t	3913	4002	3765	3872
		f_f	4031	3926	3814	3805
		f_t		3924	3818	

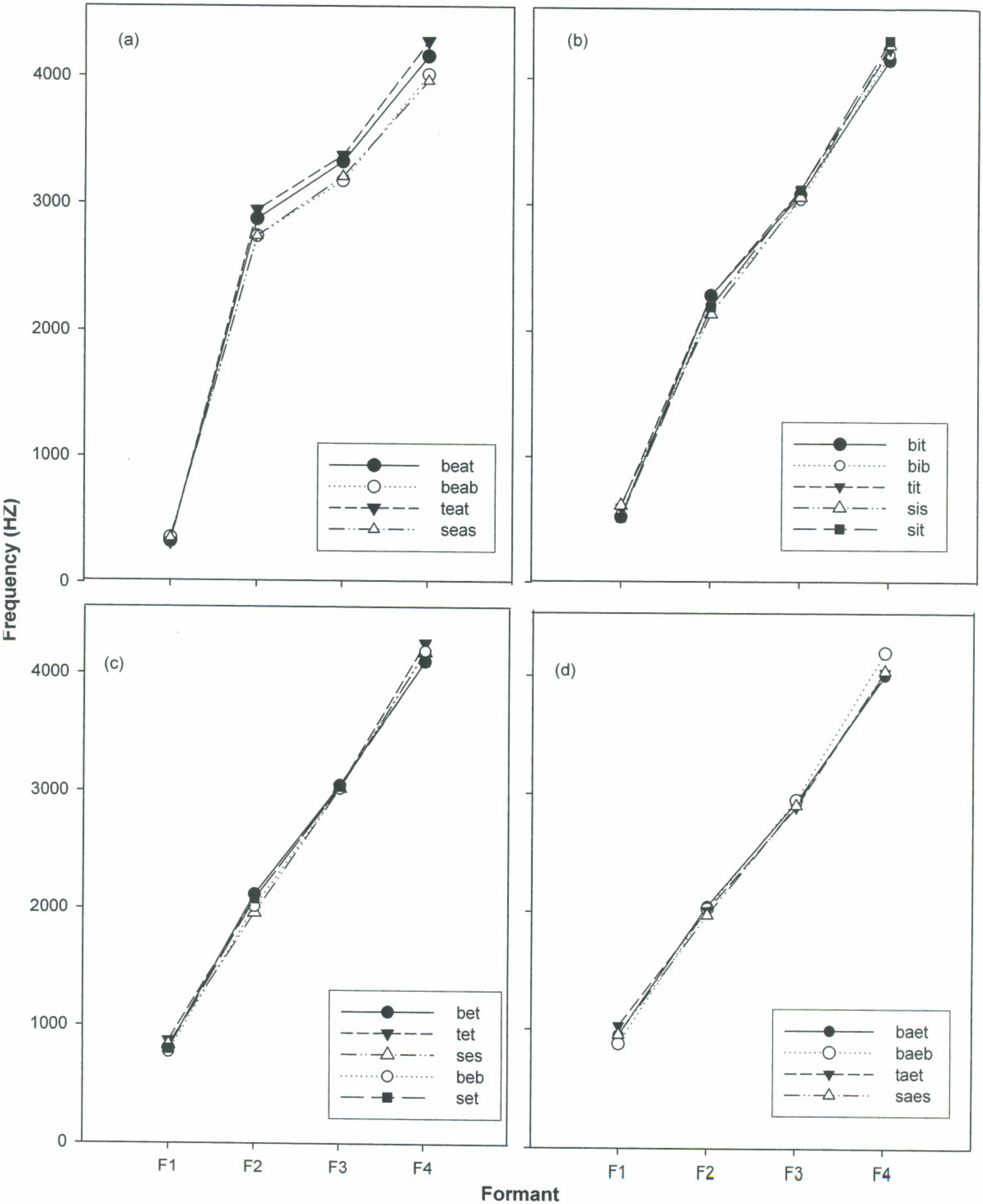


Figure 3.5. F1-F4 for female front vowels.

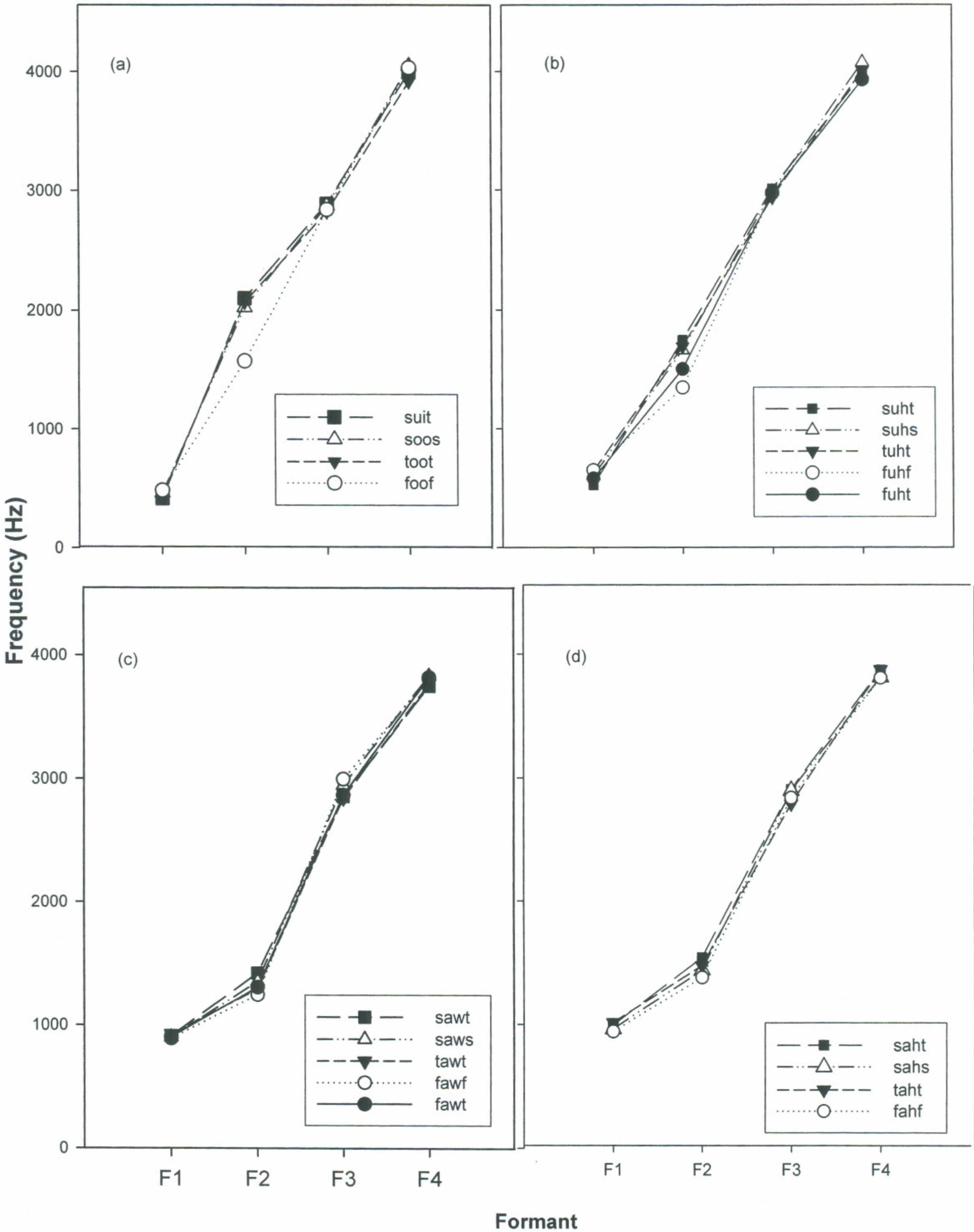


Figure 3.6. F1-F4 for female back vowels.

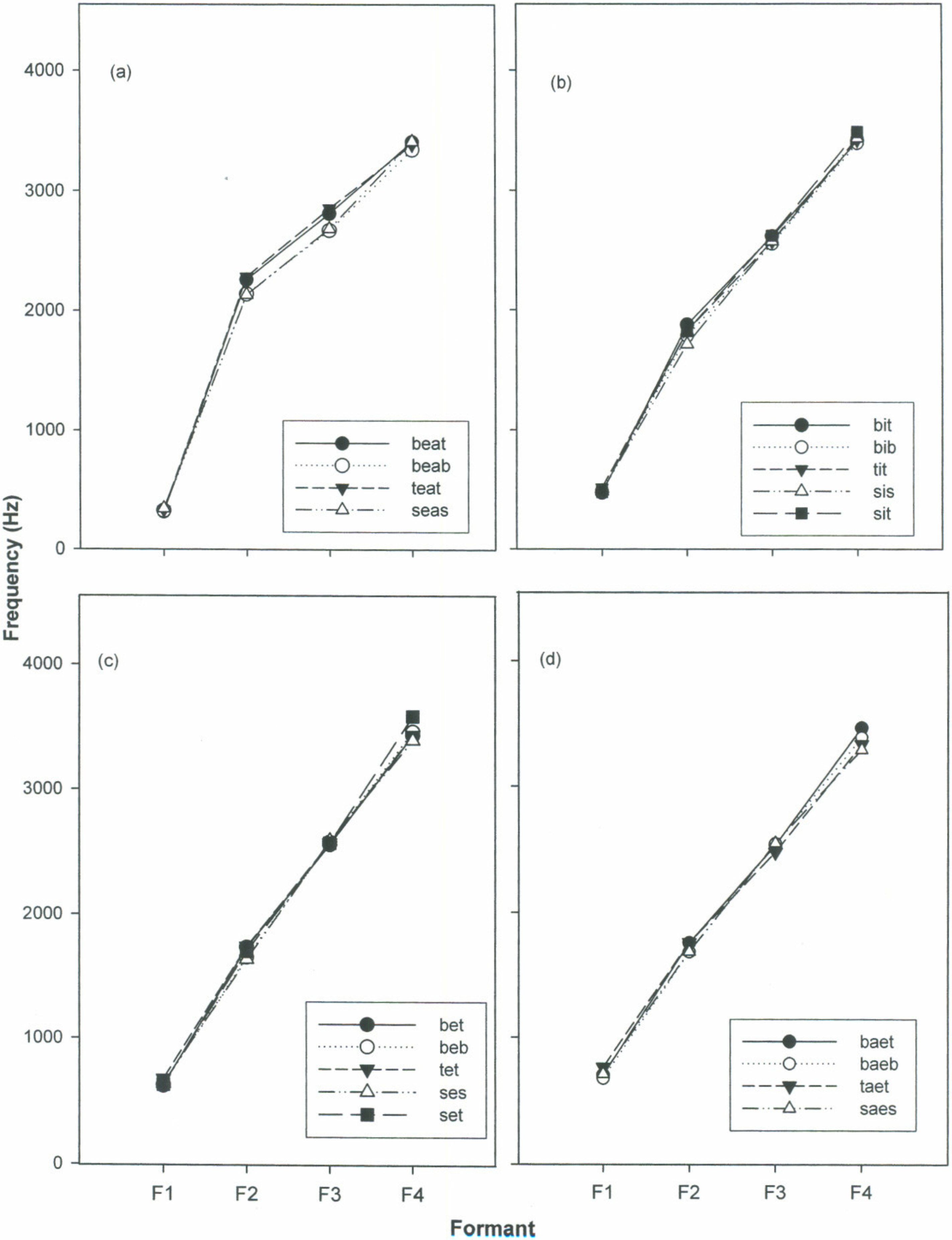


Figure 3.7. F1-F4 male front vowels.

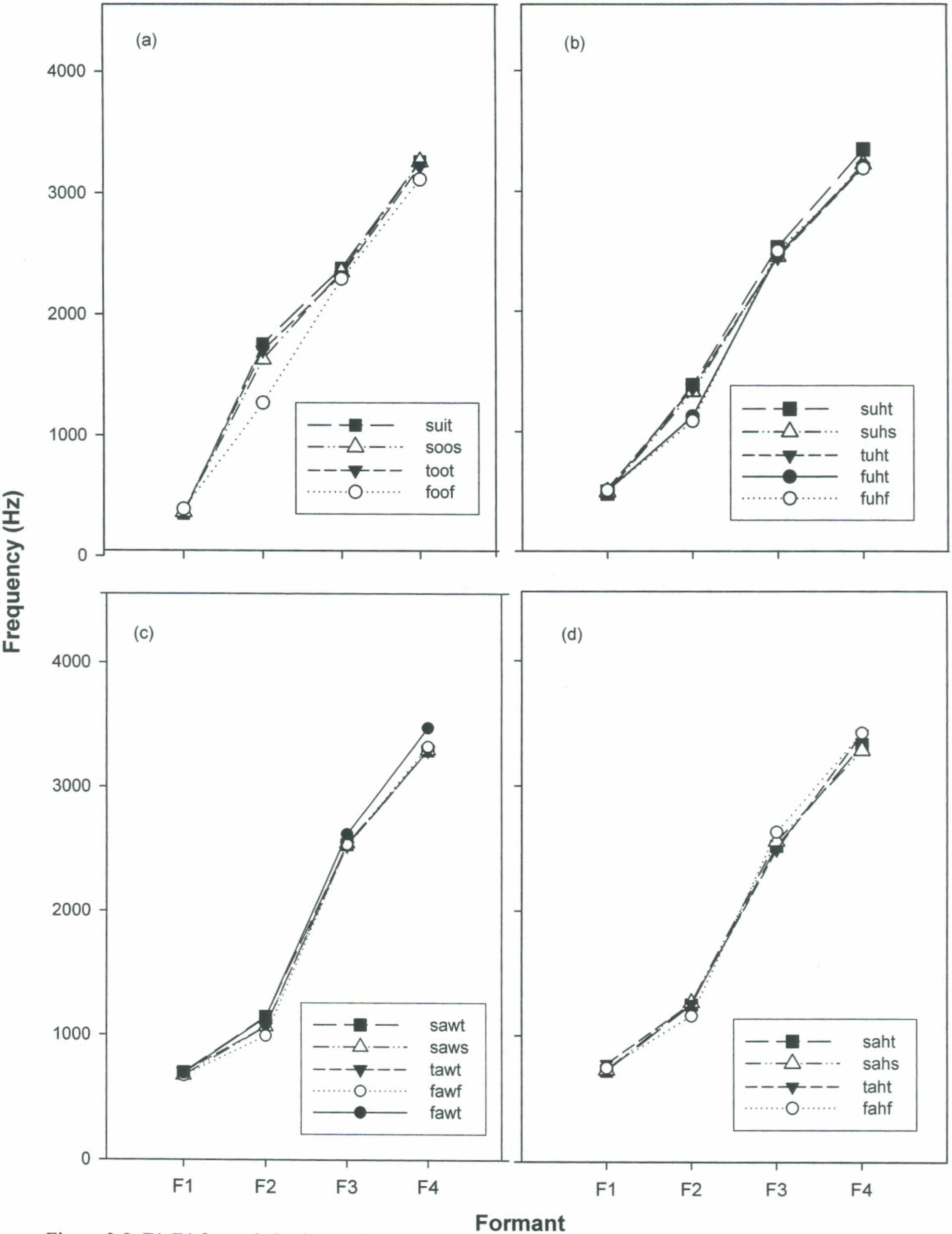


Figure 3.8. F1-F4 for male back vowels.

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